Observation of an Exotic Baryon with $S = +1$ in Photoproduction from the Proton

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The reaction $\gamma p \to \pi^+ K^- K^+ n$ was studied at Jefferson Lab using a tagged photon beam with an energy range of 3-5.47 GeV. A narrow baryon state with strangeness S=+1 and mass $M = 1555 \pm 10$ MeV/c^2 was observed in the nK^+ invariant mass spectrum. The peak's width is consistent with the CLAS resolution (FWHM=26 MeV/c^2), and its statistical significance is $7.8 \pm 1.0\ \sigma$. A baryon with positive strangeness has exotic structure and cannot be described in the framework of the naive constituent quark model. The mass of the observed state is consistent with the mass predicted by the chiral soliton model for the Θ^+ baryon. In addition, the pK^+ invariant mass distribution was analyzed in the reaction $\gamma p \to K^- K^+ p$ with high statistics in search of doubly-charged exotic baryon states. No resonance structures were found in this spectrum.

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The constituent quark model describes light mesons as bound states of a quark and an antiquark ($q\bar{q}$), and baryons as bound states of three quarks (qqq), where q is u, d or s. It is a remarkable feature of meson and baryon spectroscopy that practically all well-established particles can be categorized using this naive model. At the same time, Quantum Chromodynamics (QCD) predicts the existence of so-called exotic mesons and baryons with more complicated internal structures. Exotic mesons may be classified such as glueballs (ggg), hybrids ($q\bar{q}g$), and four–quark ($q\bar{q}q\bar{q}$) states, and exotic baryons as ($qqqg$) or ($qqqq\bar{q}$) states.

A baryon with strangeness quantum number $S = +1$ is an excellent example of a particle whose exotic structure is manifest. Diakonov, Petrov, and Polyakov [1], in the framework of the chiral soliton model, have predicted a spin 1/2, isospin 0, and strangeness $S = +1$ exotic baryon Θ^+ with mass $M \sim 1.53$ GeV/c^2. Also, the pentaquark states was considered in the quark models [2] and lattice QCD [3]. The possible quark structure of Θ^+ is ($uudd\bar{s}$).

Experimental evidence for a narrow $S = +1$ baryon state has been reported in the interactions of photons and kaons with nuclear targets: $\gamma n \to K^+ K^- n$ (on a ^{12}C target) [4], $K^+ Xe$ collisions in the pK^0 decay mode [5], and the exclusive photo-deuteron interaction in the nK^+ decay mode [6]. In all these reactions the primary interaction is with a neutron in the initial state. The CLAS collaboration has reported the observation of the same state in the photoproduction reaction from the proton target [7]. The SAPHIR collaboration [8] has also reported the observation of this state in the reaction $\gamma p \to n K^+ K^0_s$. A narrow peak with mass around $M = 1.54$ GeV/c^2 and width less than 25 MeV/c^2 was observed, and interpreted as the production and decay of the exotic Θ^+ baryon. More recently, the ITEP collaboration observed a narrow baryon resonance in the invariant mass of the pK^0_S system formed in neutrino and antineutrino collisions with nuclei [9].

This letter reports a more comprehensive study than in [7] of the Θ^+ production on a proton target which includes data from three distinct runs under different experimental conditions in CLAS [10]. Two reactions, $\gamma p \to \pi^+ K^+ K^- n$ and $\gamma p \to K^+ K^- p$, have been analyzed. Of the three runs, *Run a* and *Run b* had identical geometrical acceptance and trigger requirement with *Run c* having slightly different running conditions. *Runs a, b* and *c* had a tagged photon beam in the energy range of 3.2–3.95 GeV, 3–5.25 GeV, and 4.8–5.47 GeV, respectively [11]. CLAS is a six-fold segmented toroidal magnetic spectrometer (details described in [10]). *Run c* triggered on the events with at least 2 out of 6 CLAS sectors having charged tracks, while *Runs a* and *b* triggered on events with hits in opposite sectors. *Runs a* and *b* had the hydrogen target in the standard position, but in *Run c* the target was moved upstream by 1 meter to improve the CLAS acceptance in the forward direc-

*Deceased

tion, especially for the negative charged particles. The estimated integrated luminosity for the combined data of *Runs a* and *b* is 2 pb^{-1}, and *Run c* is 2.7 pb^{-1}. The combined analysis of these three runs offers access to a wider range of acceptance and energies.

Events having a π^+, K^+, and K^- in the final state, identified by time-of-flight, were selected for the analysis of the reaction $\gamma p \to \pi^+ K^- K^+ n$. The missing mass distributions for the reaction $\gamma p \to \pi^+ K^- K^+ X$ are shown in Fig. 1. A neutron peak is clearly seen in each of these

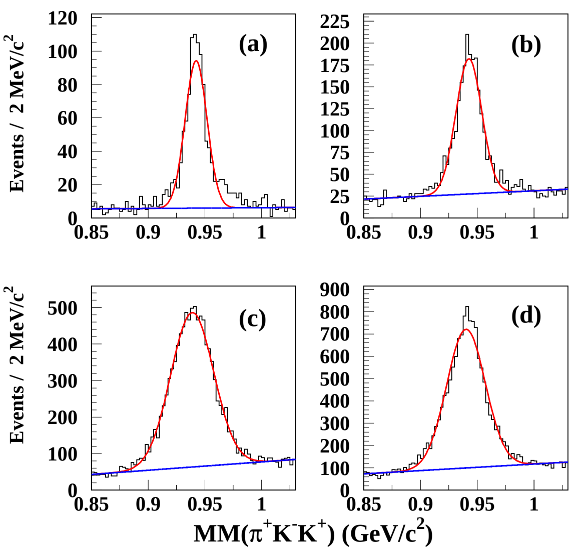

FIG. 1: The missing mass distributions in the reaction $\gamma p \to \pi^+ K^- K^+ X$ for the three different runs (*Runs a*,*b*, and *c*) and the combined data spectrum (*d*). The mass resolutions are 10, 11, and 19 MeV/c^2 for *Runs a*, *b*, and *c* respectively.

distributions. The fitted masses of the neutron peaks are consistent with each other within 3 MeV/c^2. The mass resolution for *Runs a* and *b* is about twice as good as in *Run c* due to the fact that *Run c* had higher energy and the magnetic field was reduced by a factor of 2. Events within $\pm 2\sigma$ of the neutron peak were retained for each run individually, resulting in a total of 14k events.

There are about 200 ϕ mesons in the selected sample, which were removed by eliminating events with the K^+K^- effective mass less than 1.06 GeV/c^2. The final nK^+ invariant mass spectrum calculated from missing mass in the reaction $\gamma p \to \pi^+ K^- X$, combining data from all three data runs, is shown in Fig. 2. No obvious structure is seen in this spectrum.

We explored various possible t-channel processes to understand the potential production mechanisms for the Θ^+ as well as the background, examples of which are illustrated in Fig. 3. A peak appears most clearly when requiring $\cos\theta^*_{\pi^+} > 0.8$, where $\theta^*_{\pi^+}$ is the center-of-mass angle between the π^+ and the photon beam. This requirement approximately corresponds to $-t < 0.28$ GeV/c^2

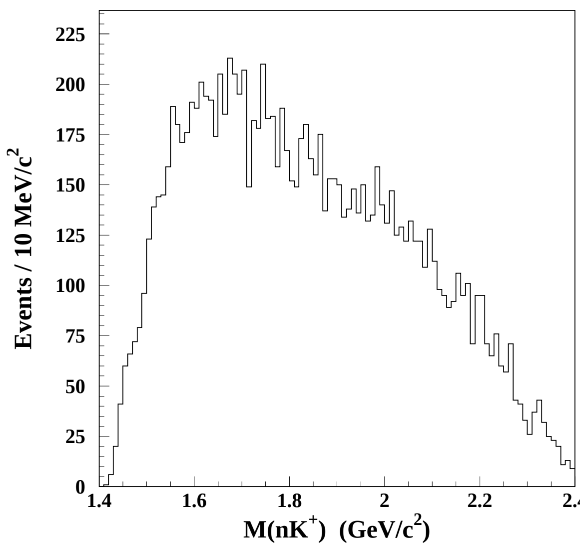

FIG. 2: The nK^+ invariant mass spectrum in the reaction $\gamma p \to \pi^+ K^- K^+(n)$. The neutron was measured from the missing four-momentum.

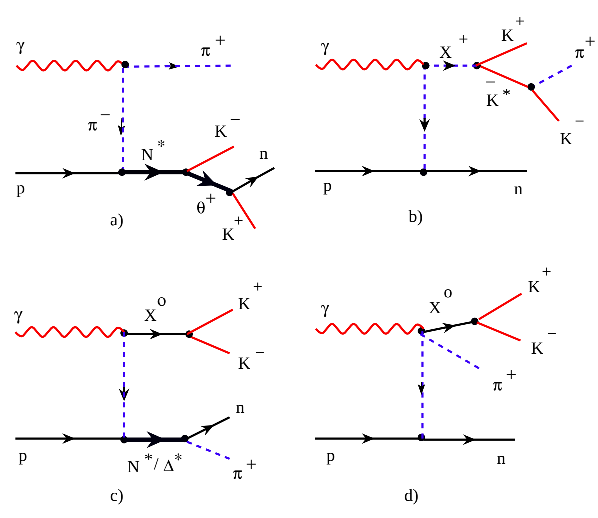

FIG. 3: The diagram in (*a*) shows a possible production mechanism for the Θ^+, which could be a decay product of an intermediate baryon resonance. The three diagrams in (*b*), (*c*), and (*d*) are background processes in the reaction $\gamma p \to \pi^+ K^- K^+(n)$. All background processes have a K^+ going in the forward direction in the center-of-mass system.

where $t = (k-p)^2$, k is the photon 4-momentum, and p is the pion 4-momentum. This would correspond to an enhancement of the t-channel process as shown in Fig. 3 *a*. The spectrum is shown in the inset in Fig. 4. As a systematic check, we varied the pion angular cut from 0.7

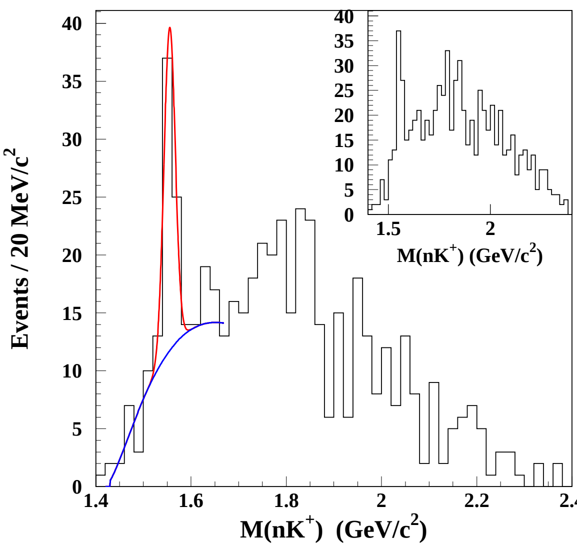

FIG. 4: The nK^+ invariant mass spectrum in the reaction $\gamma p \to \pi^+ K^- K^+(n)$ with the cut $\cos\theta^*_{\pi^+} > 0.8$ and $\cos\theta^*_{K^+} < 0.6$. $\theta^*_{\pi^+}$ and $\theta^*_{K^+}$ are the angles between the π^+ and K^+ mesons and photon beam in the center-of-mass system. The background function we used in the fit was obtained from the simulation. The inset shows the nK^+ invariant mass spectrum with only the $\cos\theta^*_{\pi^+} > 0.8$ cut.

to 0.9 and found that in all cases the peak was clearly visible.

The background reaction $\gamma p \to \pi^+ K^- K^+ n$ is dominated by meson resonance production decaying to K^+K^- with the excitation of baryon resonances decaying to $n\pi^+$, or meson resonance production decaying to $K^+K^-\pi^+$, both with small momentum transfer to the meson system. These processes have the K^+ moving forward in the center-of-mass system (Fig. 3 b, c and d). To suppress such backgrounds, a cut was applied to eliminate events having a positive kaon going forward with $\cos\theta^*_K > 0.6$, where $\theta^*_{K^+}$ is the center-of-mass angle between the K^+ and the photon beam. The remaining data sample is virtually free of the contaminating events that have baryons decaying to $n\pi^+$ in this final state since the π^+ from such event will most likely not move very forward in the center-of-mass system. The Θ^+ peak was clearly observed in each of the three data sets; the resulting nK^+ mass spectrum are combined and shown in Fig. 4.

An investigation has been conducted to test whether a narrow peak in the nK^+ invariant mass spectrum can be artificially manufactured. First, we checked the sidebands around the neutron in Fig. 1; the resulting nK^+ effective mass distribution is structureless. We also considered the effect of the kinematic requirements that we applied by performing a Monte Carlo simulation based on $nK^+K^-\pi^+$ 4-body phase space, $nK^+\bar{K}^*_0$ 3-body phase space, and t-channel meson production. The meson events in the latter process are generated using $K^+K^-\pi^+$ 3-body phase space and the shape of the $K^+K^-\pi^+$ invariant mass distribution from the data. We found no structure generated using the same cuts on the simulated events as applied on the data. Furthermore, one may consider whether some particular combination of meson waves can be reflected as a narrow peak in the nK^+ invariant mass distribution. We performed a full partial wave analysis of the $K^+K^-\pi^+$ meson system on *Run c* data and utilized the prediction of this analysis to further probe the possibility of meson reflection into the nK^+ invariant mass spectrum. Again, we found that with a set of meson partial waves that well describes the entire data set we did not generate a narrow Θ^+ peak when the same angular cuts as above are applied.

The final nK^+ effective mass distribution (Fig. 4) was fitted by the sum of a Gaussian function and a background function obtained from the simulation. The fit parameters are: $N_{\Theta^+} = 41 \pm 10$, $M = 1555 \pm 1$ MeV/c^2, and $\Gamma = 26 \pm 7$ MeV/c^2 (FWHM), where the errors are statistical. The systematic mass scale uncertainty is estimated to be ± 10 MeV/c^2. This uncertainty is larger than our previously reported uncertainty [6] because of the different energy range and running conditions, and is mainly due to the momentum calibration of the CLAS detector and the photon beam energy calibration. The statistical significance for the fit in Fig. 4 over a 40 MeV/c^2 mass window is calculated as $N_P/\sqrt{N_B}$, where N_B is the number of counts in the background fit under the peak and N_P is the number of counts in the peak. We estimate the significance to be $7.8 \pm 1.0\,\sigma$. The uncertainty of $1.0\,\sigma$ is due to the different background functions that we tried. When a simple polynomial background is used, the statistical significance is higher. In the present analysis we used the background function obtained from the simulation as discussed above. The fact that the angular cuts we applied enhanced the Θ^+ signal suggests the possible production of an N^*/Δ^* that decays to Θ^+ and K^-. If the Θ^+ is an isosinglet, the intermediate state can only be an N^*. The nK^+K^- invariant mass is shown in Fig. 5 for the events with nK^+ effective mass between 1.54 and 1.58 GeV/c^2. The apparent excess of events near 2.4 GeV/c^2 is suggestive of an intermediate baryon state. A possible production mechanism that could contribute to the Θ^+ production is shown in Fig. 3 a. Similar processes were also theoretically considered in Ref. [12]. The simulation we described previously also demonstrated that the angular cuts we applied could not generate a narrow peak in the nK^+K^- invariant mass spectrum from any of the three data runs.

In addition, a search for a manifestly exotic baryon ($Q = 2$, $S = +1$) was performed in the reaction $\gamma p \to K^- X^{++}$, $X^{++} \to pK^+$. There were 225k events with a proton and K^+ in the final state, which were selected for the analysis of this reaction. The K^- was identified by

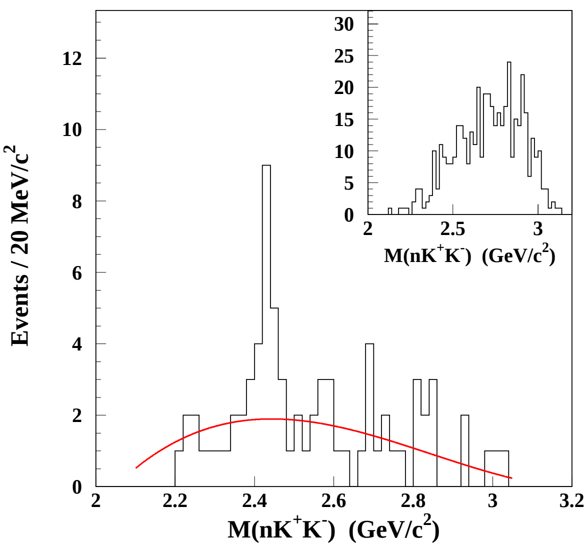

FIG. 5: The nK^+K^- invariant mass spectrum calculated from the missing mass off the π^+ in the reaction $\gamma p \to \pi^+ K^- K^+ (n)$ with the cuts $\cos\theta^*_{\pi^+} > 0.8$ and $\cos\theta^*_{K^+} < 0.6$. $\theta^*_{\pi^+}$ and $\theta^*_{K^+}$ are the angles between the π^+ or K^+ mesons and photon beam in the center-of-mass system. These events have $M(K^+n)$ between 1.54 and 1.58 GeV/c^2. The shape of the background curve was obtained from the simulation as discussed in the text. The inset shows the nK^+K^- invariant mass spectrum for all other events in Fig. 4.

the missing mass technique. After the removal of $\phi \to K^+K^-$ and $\Lambda(1520) \to K^-p$, we observe no resonant structures in the pK^+ invariant mass distribution for the remaining 130k events. The pK^+ invariant mass spectra for different $\cos\theta^*_{K^-}$ were analyzed as well, where $\theta^*_{K^-}$ is the angle between the K^- and incident photon in the center-of-mass system. There are no resonance structures evident in any of these distributions. A more detailed analysis will be presented in a future paper.

In summary, the reaction $\gamma p \to \pi^+ K^- K^+ n$ was studied at Jefferson Lab with photon energies from 3 to 5.47 GeV using the CLAS detector. A narrow baryon state with positive strangeness $S = +1$, mass $M = 1555 \pm 10$ MeV/c^2 and width $\Gamma < 26$ MeV/c^2 (FWHM) was observed. The width is close to the experimental mass resolution of the CLAS detector. The peak's statistical significance is $7.8 \pm 1.0\ \sigma$. In addition, the pK^+ invariant mass distribution was analyzed in the reaction $\gamma p \to K^- K^+ p$ with high statistics. No resonance structures were found in this spectrum.

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